APPENDIX 9.C — SEDIMENT DEPOSITION IN CULVERTS

9.C.1 INTRODUCTION

A concern with culverts, particularly improved inlet or high-velocity culverts, is problems associated with the adverse deposition of sediment. Unexpected and excessive deposition might block a portion of the culvert inlet, barrel or outlet. Such blockage might not be scoured out in time during the rising limb of the hydrograph to avoid a flood hazard. This is one reason it is sometimes necessary to make an assessment of potential sediment problems at a culvert. Sedimentation can also be a costly maintenance problem where flood hazards are not involved, particularly with combined drainage and land-use structures.

First, it is necessary to make an assessment of the channel reach's morphology to ascertain its influence on sediment deposition at the culvert site. A degrading stream normally does not cause a sediment deposition problem at the outlet, although the degradation may result in sufficient sediment supply to the inlet to where a deposition problem might occur at that point. Conversely, aggrading streams usually cause deposition, starting downstream and extending upstream through the culvert.

9.C.2 SEDIMENT TRANSPORT

Whether sediment will deposit or be scoured out of a culvert depends upon the relative abilities of the upstream channel and the culvert to transport sediment under the combinations of conditions that occur at a particular site.

The rate at which transported sediment arrives at the culvert depends on whether it is from the:

- upstream reach, or
- reservoir outflow.

UPSTREAM REACH. Where temporary upstream ponding does not occur or is limited, the transport rate arriving at the culvert is approximately the same for the upstream reach. This rate can be estimated using the sediment transport practices found in Reference *(1)*, Section 9.C.6. USGS also has sediment transport records on selected streams and rivers. These records and/or bed sampling will provide the geometric characteristics of the sediment.

RESERVOIR OUTFLOW. Significant temporary upstream ponding may alter the sediment transport rate in the upstream reach. This ponding may cause the coarser sediment fraction to deposit in the temporary pond. If this is expected to occur, a sediment routing analysis through the temporary pond is required to estimate the sediment transport rate and characteristics reaching the culvert.

Deposition in a culvert occurs until either:

- the flood ceases,
- sufficient hydraulic change occurs to where deposition in the culvert ceases, or
- the culvert becomes blocked.

9.C.3   HYDRAULIC CHANGE

Two common hydraulic changes are gradient and friction:

GRADIENT. This change is where the culvert fills with sediment to where a hydraulic gradient develops sufficiently to preclude further deposition. This would be evidenced in a return of the Sediment Transport Ratio (R_G) to unity or less, in which case the sediment deposited in the culvert would begin to be removed by scour. This can be expected where the deposited sediment gradient is approximately the same as the natural stream channel gradient that would exist if the culvert were not in place. Where a channel is determined to be unstable, this gradient would be the regime slope for the discharge in question.

FRICTION. This change relates to the Manning's friction value in the culvert, n_2. As sediment is deposited, this friction value changes. Bed forms may be part of this change.

9.C.4   ASSESSMENT TYPES

Four types of assessments are considered in this *Manual*:

- statistical,
- simplistic,
- complex, and
- tractive shear.

It should not be expected that the findings obtained with these four assessment types will be in agreement. The science is too poorly defined at this time. Accordingly, engineering judgment is essential in interpreting the findings from each assessment and in resolving the differences. When in doubt and where the site circumstances are sensitive, the more conservative finding that has an element of credibility is recommended.

9.C.4.1   Statistical Assessment

A statistical assessment provides a rough estimate of future deposition and scour patterns in a culvert. This is because natural flows do not remain steady for any prolonged period of time and may occur in an infinite variety of patterns and amplitudes. This practice is complex and thus not appropriate for most culvert designs. Statistical assessments are currently beyond the scope of this *Manual*.

9.C.4.2   Simplistic Assessment

Usually a more simplistic assessment will usually suffice, unless there are extenuating circumstances dictating a complex assessment. The simplistic assessment is based on extreme conditions. It is assumed that the culvert barrel will fill beyond the point at which the channel replaced by the culvert would have filled had the culvert not been constructed. It must be recognized that this filling may be above the apparent natural flow line of the stream at the time of the survey if the natural channel was unstable and in the process of aggrading at the time the culvert was constructed; with degradation, the converse would be expected. Except for unstable, aggrading channels, the existing channel flow line is assumed to be the limit of deposition. Figure 9.C-1 illustrates this concept.
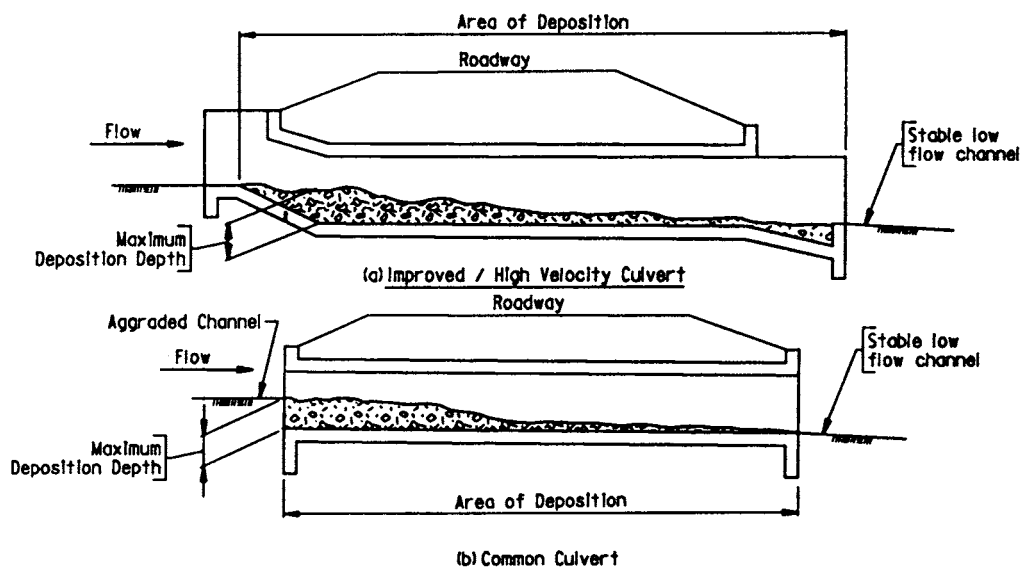
FIGURE 9.C-1 — Culvert Sediment Deposition

A simple expression is needed that will allow a quick assessment to be made. It is instructive to analyze this problem using one of the more simple analytical expressions for sediment transport. Using the DuBoy's formula and the Manning formula for both the channel upstream from the culvert and for flow through the culvert, the following equation can be developed for streams and culverts in the general case:

$$R_G = (q_s/q)_1/(q_s/q)_2 \tag{9.C.1}$$
$$R_G = (V_1/V_2)^3(n_1/n_2)^4(y_2/y_1)^{5/3} \ ... \ [(1 - S_c/S_1)/(1 - S_c/S_2)] \tag{9.C.2}$$

where: (q_s/q) =   ratio of sediment discharge to water discharge
$V_{1,2}$ =   average velocity in uniform flow, ft/s
$n_{1,2}$ =   Manning's n
$y_{1,2}$ =   average depth of uniform flow, ft
$S_{1,2}$ =   slope of the hydraulic grade line, ft/ft
R_G =   sediment transport ratio
S_c =   critical slope at which sediment of a given size begins to move, ft/ft

In this expression, the subscript 1 refers to the reach upstream of the culvert, and the subscript 2 refers to a location within the culvert.

In nearly all streams where flood flows are many times larger than ordinary low flows, the terms involving S_c and S may be dropped from the expression because the value of S_c is small compared to either of the S values. This results in ratios equal to unity. Thus, Equation C.2 reduces to:

$$R_G = (V_1/V_2)^3(n_1/n_2)^4(y_2/y_1)^{5/3} \tag{9.C.3}$$

If the ratio R_G is greater than unity (with Section 1 being upstream from Section 2), deposition will occur in the vicinity of Section 2. Where R_G is much greater than unity, expect nearly all of the sediment carried by the stream to be deposited; Example problem 1 illustrates this concept.

As suggested by Figure 9.C-1, an acceptable deposition depth should be much less than the barrel height. The deposition in all channels except unstable, aggrading channels is assumed to be less than this depth if the velocity in the barrel at ordinary discharges is greater than that in the upstream channel, and the n values and flow depths are of the same order of magnitude. *Caution: Having the same sediment properties does not always imply the same n values because bed forms may only exist upstream or in the culvert.*

9.C.4.3 Complex Assessment

Of concern is whether a proposed or existing culvert partially filled with sediment will be scoured out on the rising limb of the hydrograph before the design high-water level is reached. This depends upon the ability of the flow in the culvert barrel to remove sediment. A more complex assessment is required in this instance.

In this assessment of various size, fractions are routed through the site using finite time elements. This requires estimates of the inflow hydrograph to the site, flood routing through the culvert to obtain the outflow hydrograph, the sediment transport rate arriving at the culvert, the sediment transport rate through the culvert and a flood discharge versus sediment discharge relationship. The hydrograph can be estimated using the practices in the Hydrology Chapter. Culvert flood routing is addressed in Section 9.9 of this Chapter.

Reference *(1)*, Section 9.C.6 sets forth a sediment transport equation for an enclosed culvert. The reliability of this equation is marginal due to the complexities associated with inlet and outlet control flow conditions. This equation is provided as Equation C.4, which is used to estimate the sediment transport rate through a round culvert flowing full. Structures not flowing full or not round in shape must have an equivalent full flow, round geometry estimated for each incremental time increment used in the sediment routing procedure:

$$Q_{SMAX} = 3.78(g)^{0.5}D_s^{-1.02}S_f^{2.52}R^{1.52}A \qquad\qquad (9.C.4)$$

where: Q_{SMAX} =   sediment discharge rate in volume per time through the culvert, ft³/s

D_s =   median sediment diameter of the size fraction under consideration, ft

R   =   equivalent hydraulic radius for barrel flow (A/P), ft

A   =   equivalent full flowing, round culvert area for the actual barrel flow depth, ft²

P   =   equivalent full flowing, round culvert wetted perimeter for the actual barrel flow depth, ft

S_f =   culvert slope, ft/ft

g   =   gravity, 32.2 ft/s²

When Q_{SMAX} is less than the sediment transport rate arriving at the culvert, Q_s, deposition will occur in the culvert barrel and upstream.

Deposition will reduce the culvert opening, thereby increasing the upstream backwater above that which would have been expected. This circumstance will also occur if the downstream channel reach's sediment transport is less than the upstream channel reach's sediment

transport. The converse is true if the Q_{SMAX} and downstream channel reach's sediment transport is greater than the upstream channel's sediment transport rate. To be considered, at least subjectively, is the potential for the upstream delta due to deposition within the temporary pond migrating downstream and subsequently blocking the culvert entrance.

9.C.4.4 Tractive Shear

A relatively subjective assessment using tractive shear practices may prove instructive. Using the morphology concepts and practices found in Reference *(1)*, Section 9.C.6, estimate a regime slope for the channel reach where a culvert is to be constructed or where a culvert experiencing sedimentation problems is located. Superimpose this expected regime slope on the culvert. Allowances must be made for expected aggradation or degradation.

Using small, frequently occurring discharges (e.g., the annual or mean annual discharge), estimate the probable tractive shear for this expected regime slope. This shear is determined using Equation 9.C.5:

$$\tau = \gamma DS \qquad\qquad\qquad (9.C.5)$$

where: τ = shear against bed (for small slopes), lbs/ft^2
          γ = unit weight of water, 64.4 lbs/ft^3
          D = depth of flow, ft
          S = expected regime slope, ft/ft

Again from Reference *(1)*, Section 9.C.6, select the critical tractive shear, τ_c, for the sediment expected to be deposited in the culvert (usually, the same material as the streambed is used for this selection). If the computed τ for low discharges is much greater than the selected τ_c, then deposition problems are less likely to occur. Should τ and τ_c be relatively close, the Complex Assessment may be justified.

9.C.5 EXAMPLES

9.C.5.1 Example 1 — Simplistic Assessment

Consider a smooth culvert. Given the data in Table 9.C-1, compute R_G using Equation 9.C.3.

TABLE 9.C-1 — Hydraulic Properties

Q (ft^3/s)	V$_1$ (ft/s)	V$_2$ (ft/s)	n$_1$	n$_2$	Y$_1$ (ft)	y$_2$ (ft)	R$_G$
100	1.0	1.0	0.045	0.030	3.0	1.0	0.81
500	2.0	12.0	0.045	0.015	5.0	3.0	0.16
1500	3.0	24.0	0.045	0.015	8.0	6.0	0.10

100 ft^3/s Discharge. The high value of R_G indicates that nearly all of the sediment carried by the stream would be deposited. This would occur until such time as the deposition either (1) created sufficient hydraulic change to where deposition in the culvert ceased, or (2) blocked the culvert. The hydraulic change would be where the culvert was totally or partially filled with sediment to establish a gradient approximately the same as that which exists had the culvert not been constructed. As such, filling can be expected to take place, the effective n value for the culvert

gradually increase, and the depth of flow gradually decrease until equilibrium is reached. Note that an n value of 0.030 was used for this smooth culvert at this discharge. This is to allow for the added roughness of sediment deposited in the culvert and perhaps bed forms.

500 ft^3/s Discharge. The value of R_G indicates that some scouring would take place and that, eventually, the culvert would be scoured clean if this discharge were to be maintained for a sufficient period of time. Note that the n value used for the culvert indicates the barrel to have been scoured out. If a higher n value had been inadvertently used for a barrel assuming that it was not entirely scoured out, the R_G value would have been much lower indicating a still higher rate of scour.

Consider the time required to scour out this culvert when the sediment transport rate to the culvert at a flood discharge of 500 ft^3/s is approximately 0.33 ft^3/s. If the average R_G ratio were to be 0.7 (making allowance for a period of higher n values in the culvert due to the bottom being rough with deposited sediment and perhaps bed forms), the rate of removal or scour with the discharge at Points 1 and 2 assumed to be the same would be:

$$
\begin{aligned}
R_G &= (q_s/q)_1/(q_s/q)_2 \\
R_G &= (q_s)_1/(q_s)_2 \text{ or,} \\
(q_s)_2 &= (q_s)_1/R_G \\
(q_s)_2 &= 0.33/0.7 = \text{say } 0.5 \text{ ft}^3\text{/s of sediment}
\end{aligned}
$$

The difference of approximately $0.50 - 0.33 = 0.17$ ft^3/s represents the rate at which the volume of sediment in the barrel of the culvert would decrease under these assumed conditions. In one hour at this rate, (0.17 ft^3/s)(60 min)(60 s) = 612 ft^3 of sediment would be removed. In a culvert 200 ft long, this would amount to an average area of approximately 3 ft^2 of sediment.

1500 ft^3/s Discharge. Similarly, the net rate of removal of sediment from the barrel would be approximately 3 ft^3/s of sediment. In one hour, approximately 10,000 ft^3 of sediment could be removed.

This problem illustrates a simplistic reasoning process that can be used to estimate the probable nature and rate of the deposition and scour in a culvert.

9.C.5.2   Example 2 — Complex Assessment

This Example is for a proposed culvert. However, it is also suitable where an existing culvert is experiencing a sedimentation problem. Where appropriate, this Example discusses the ramifications associated with the investigation of an existing culvert.

An 8-ft × 8-ft concrete box culvert is to be placed in a channel reach experiencing high sediment transport rates. Backwater is a sensitive issue. The culvert is proposed to be placed on a 0.001 ft/ft slope. There is a concern as to whether the design event will scour out any accumulated sediment before there is damage to upstream property.

Some estimate of the amount of sediment to be expected in the culvert at the time of the 100-yr design event is needed. One approach might be to make an assessment similar to the one illustrated in Example 1, Simple Assessment. Another approach might be to use this complex assessment practice to route several frequently occurring flood events (say the mean annual and annual events) through the culvert to determine what depth of accumulated sediment might occur. Certainly any morphology findings, or experience with existing culverts in the area,
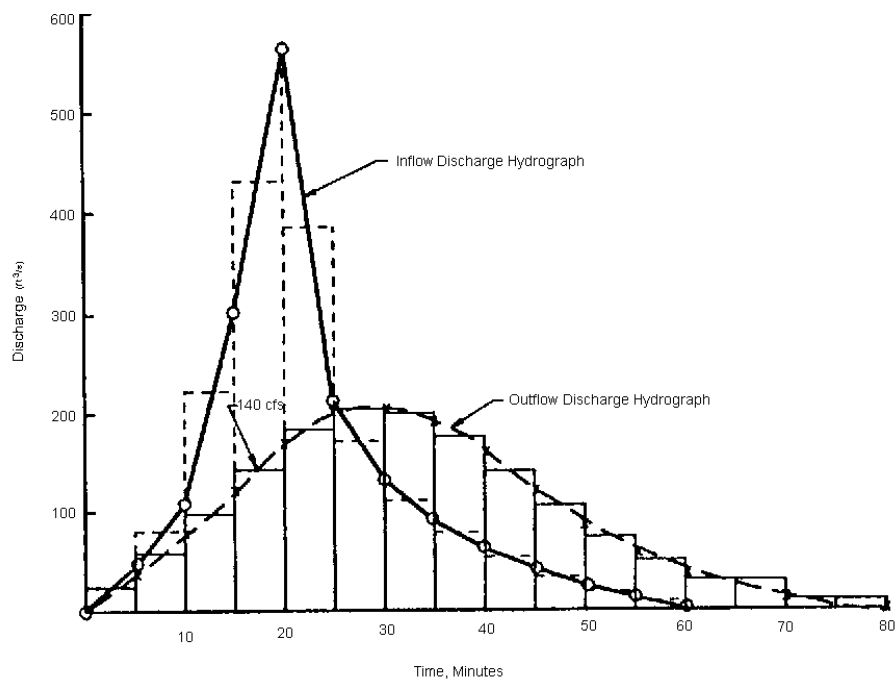
should be considered. If this was an existing culvert and there was a flood hazard concern, then in all probability the accumulated sediment depth in the culvert would be known in that it would have occurred.

9.C.5.2.1 Flood Hydrographs

A hydrology analysis (see Hydrology Chapter) provides the 100-yr design inflow hydrograph. A culvert flood routing design as described in Section 9.9 provides the outflow hydrograph. These inflow and outflow hydrographs appear in Table 9.C-2 and on Figure 9.C-2.

TABLE 9.C-2 — Design Hydrographs

Time, T (min)	Inflow Discharge, Q (ft^3/s)	Outflow, Q (ft^3/s)
0	0	0
5	38	36
10	110	80
15	300	120
20	560	170
25	210	200
30	130	205
35	90	190
40	60	160
45	40	120
50	20	80
55	10	60
60	0	40
70	0	10
80	0	0


FIGURE 9.C-2 — Design Hydrograph

9.C.5.2.2   Channel Sediment Discharge

A sediment transport analysis of the stream was made, using one of the methods in *Highways in the River Environment,* 1990 edition. In addition, USGS water quality data for similar streams was obtained. Together, these provided the estimate of sediment transport rate of the upstream reach as shown in Table 9.C-3 and on Figure 9.C-3. *Note: This transport rate was not routed through the temporary pond. By ignoring the temporary pond effect, the findings from this assessment are probably conservative.*

TABLE 9.C-3 — Sediment Discharge

| Flood Discharge Q (ft^3/s)	Sediment Discharge	
	Q_s* (mg/ℓ)	Q_s (ft^3/s)
0	0	0
10	150	0.0
30	350	0.0
50	500	0.0
100	1,200	0.0
250	3,800	0.4
350	15,100	2.0
500	23,700	4.5
600	28,000	6.4

* USGS data is usually scattered. Select data representing an upper band. It is usually necessary to convert mg/ℓ to ft^3/s. Conversion is (150 mg/ℓ)(6.245)($10^{-5}lbs/ft^3$)(10 ft^3/s)/165 lbs/ft^3 = 0.00057 ft^3/s. This assumes that the sediment weighs 165 lbs/ft^3.
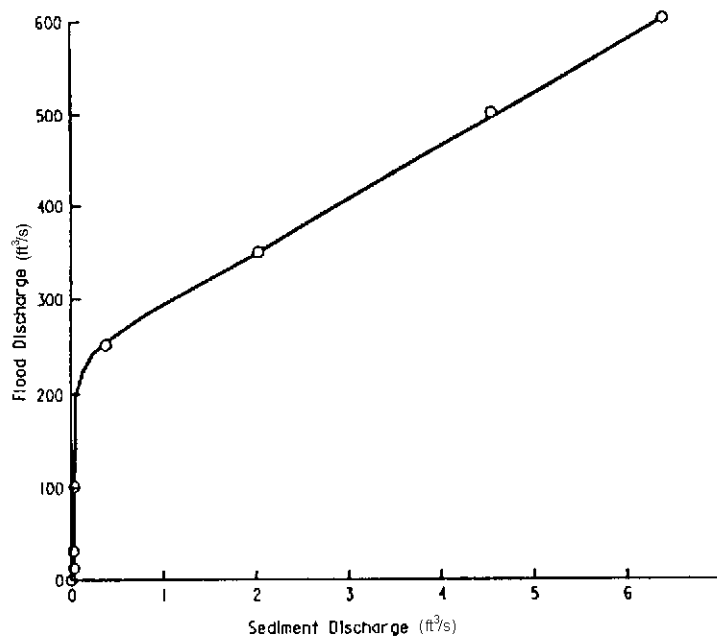
FIGURE 9.C-3 — Sediment Discharge Curve

9.C.5.2.3   Culvert Sediment Discharge

From the culvert analysis, the minimum velocity performance curve within the culvert is plotted as shown in Figure 9.C-4. Note that two curves are shown. One curve is based on sediment being deposited in the culvert bottom, thereby dictating a Manning's n of approximately 0.030. The other curve is for an n of 0.012, which presumes no sediment deposition.
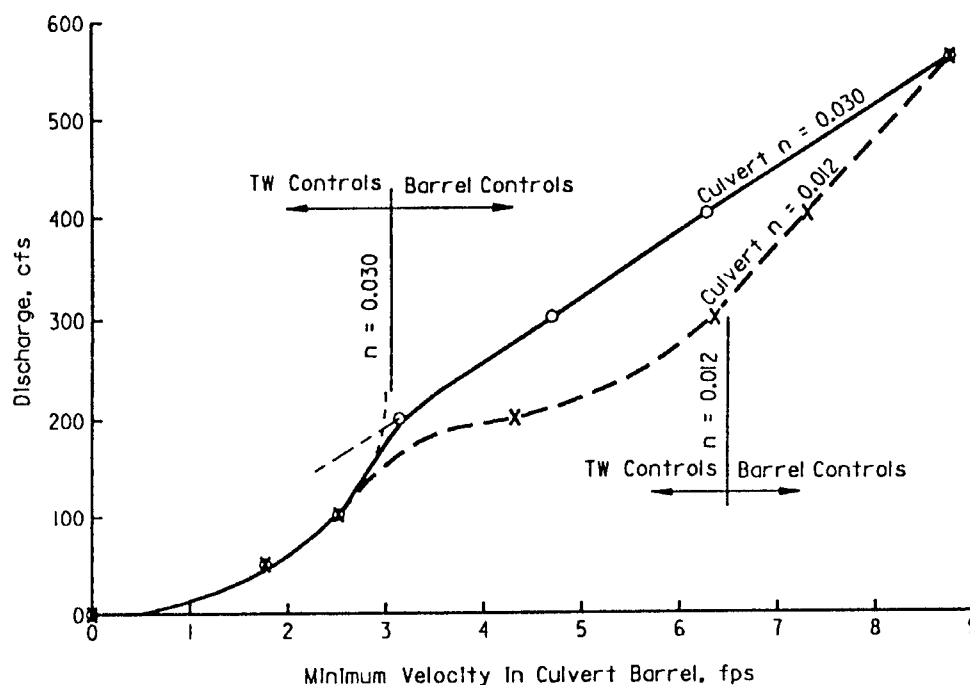
FIGURE 9.C-4 — Minimum Culvert Barrel Velocities

From Equation 9.C.4, compute the transport rate through the culvert for a range of discharges, and plot the resultant culvert sediment transport curve as Figure 9.C-5. These findings are in Table 9.C-4.

From the culvert analysis, the barrel flow depths for a Manning's n = 0.030 and 0.012 are obtained. With these flow depths, the cross sectional area, A, of the culvert is computed. Where tailwater controls (see Figure 9.C-4), those depths are used. These resulting cross sectional areas are converted into an equivalent culvert diameter based on $D = 2(A/\pi)^{1/2}$ where A = (b) (flow depth) or (8 ft)(flow depth). Using these diameters, the equivalent hydraulic radius, A/P, is computed where $P = \pi D$. Figure 9.C-5 is a plot of the data in Table 9.C-4. Only Table 9.C-4a is needed where there is no sediment deposited in the culvert (n = 0.012). However, the equivalent culvert properties are a function of the sediment deposition, thereby requiring Tables 9.C-4b through 9.C-4f for an n of 0.030. Again, these tabular findings are for an equivalent round culvert flowing full; note that the equivalent round culvert size decreases with increasing amounts of sediment being deposited in the bottom of the 8 ft x 8 ft concrete box.

TABLE 9.C-4a — Equivalent Culvert Properties (n = 0.012)

Discharge (ft³/s)	Flow Depth (ft)	A (ft²)	D (ft)	R (ft)
0	0	0	0	0
50	3.5	28	6.0	1.5
100	5.0	40	7.4	1.8
200	5.8	46	7.7	1.9
300	5.9	47	7.7	1.9
400	6.9	55	8.4	2.1
560	8.0*	64	9.0	2.3

TABLE 9.C-4b — Equivalent Culvert Properties (n = 0.030)
(Sediment Depth = 0.5 ft)

Discharge (ft³/s)	Flow Depth (ft)	A (ft²)	D (ft)	R (ft)
0	0	0	0	0
50	3.5	28	6.0	1.5
100	5.0	40	7.1	1.8
200	7.5*	60	8.7	2.2
300	7.5*	60	8.7	2.2
400	7.5*	60	8.7	2.2
560	7.5*	60	8.7	2.2

culverts flow full

TABLE 9.C-4c — Equivalent Culvert Properties (n = 0.030)
(Sediment Depth = 1ft)

Discharge (ft³/s)	Flow Depth (ft)	A (ft²)	D (ft)	R (ft)
0	0	0	0	0
50	3.5	28	6.0	1.5
100	5.0	40	7.1	1.8
200	7.0*	56	8.4	2.1
300	7.0*	56	8.4	2.1
400	7.0*	56	8.4	2.1
560	7.0*	56	8.4	2.1

TABLE 9.C-4d — Equivalent Culvert Properties (n = 0.030)
(Sediment Depth = 1.5 ft)

Discharge (ft³/s)	Flow Depth (ft)	A (ft²)	D (ft)	R (ft)
0	0	0	0	0
50	3.5	28	6.0	1.5
100	5.0	40	7.1	1.8
200	6.5*	52	8:1	2.0
300	6.5*	52	8.1	2.0
400	6.5*	52	8.1	2.0
560	6.5*	52	8.1	2.0

TABLE 9.C-4e — Equivalent Culvert Properties (n = 0.030)
(Sediment Depth = 2.0 ft)

| Discharge (ft^3/s)	Flow Depth (ft)	A (ft^2)	D (ft)		R (ft)
0	0	0	0		0
50	3.5	28	6.0		1.5
100	5.0	40	7.1		1.8
200	6.0*	42	7.8	say	1.9
300	6.0*	42	7.8	say	1.9
400	6.0*	42	7.8	say	1.9
560	6.0*	42	7.8	say	1.9

TABLE 9.C-4f — Equivalent Culvert Properties (n = 0.030)
(Sediment Depth = 3.0 ft)

Discharge (ft^3/s)	Flow Depth (ft)	A (ft^2)	D (ft)	R (ft)
0	0	0	0	0
50	3.5	28	6.0	1.5
100	5.0*	40	7.1	1.8
200	5.0*	40	7.1	1.8
300	5.0*	40	7.1	1.8
400	5.0*	40	7.1	1.8
560	5.0*	40	7.1	1.8

* Culverts flowing full.

With the data from Table 9.C-4 or Figure 9.C-5 and the slope, S$_f$, of 0.001 ft/ft, the expected sediment transport rate, Q$_{SMAX}$, for the 8-ft x 8-ft box culvert can now be computed.
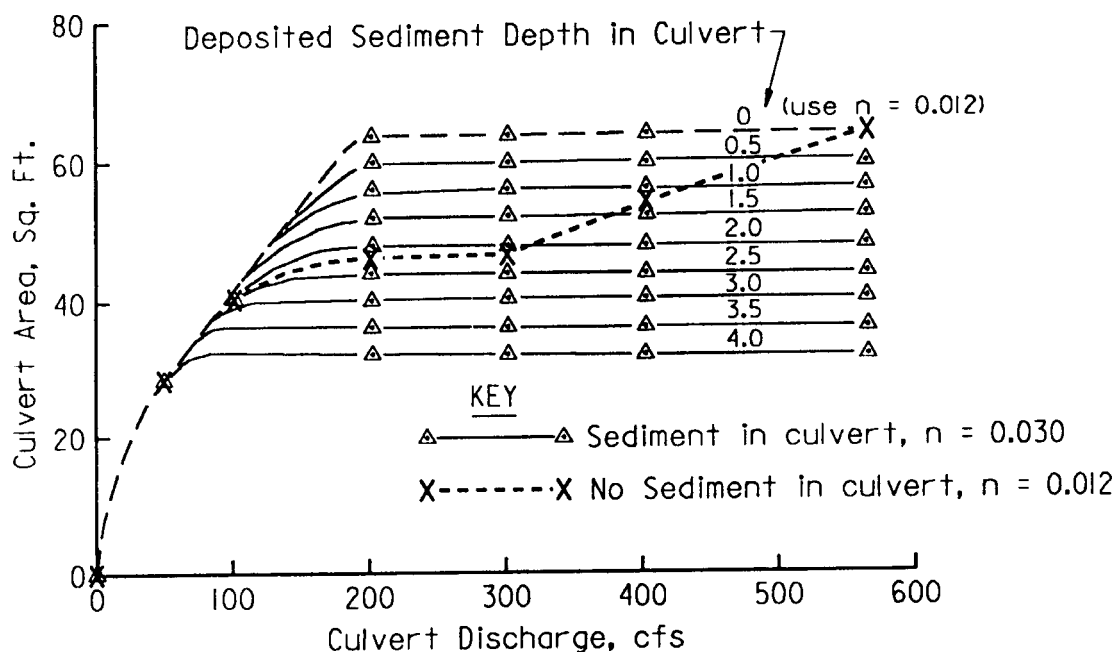
FIGURE 9.C-5a — Equivalent Area
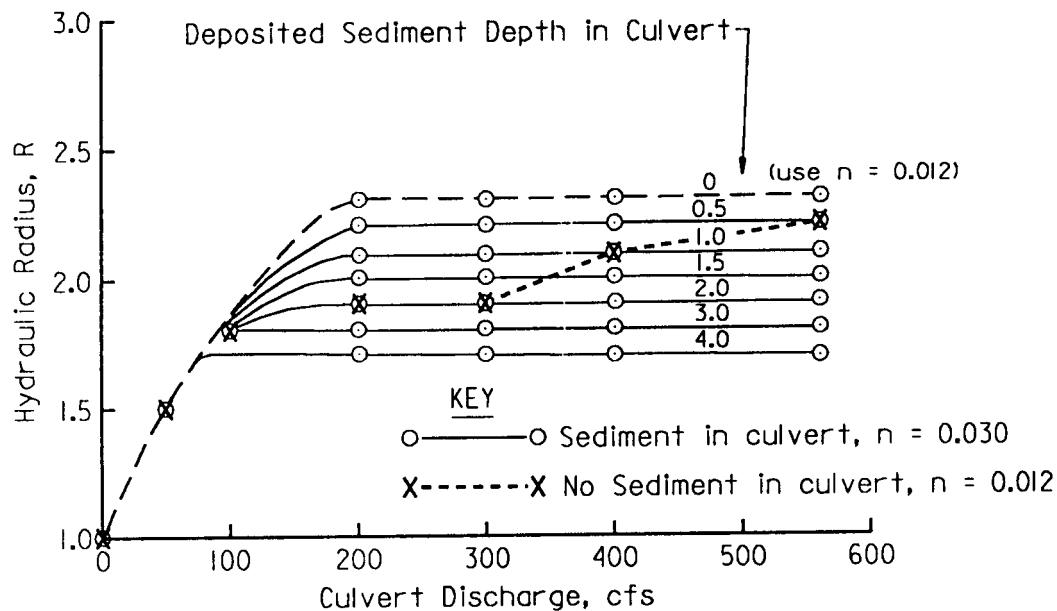
FIGURE 9.C-5b ⎯ **Equivalent Hydraulic Radius (n = 0.030)**

A streambed sample indicated that the transported sediment would have the characteristics shown in Table 9.C-5. These characteristics are assumed to be very similar to the sediment expected to be deposited inside the culvert. With a sediment deposition problem at an existing culvert, those characteristics can be determined through sampling. A difference in the transported and deposited characteristics can be important. If they are the same, the following procedure is reasonable assuming that armoring has not occurred and the deposited sediment is available for removal by scour on demand. If the transported and deposited sediment characteristics are markedly different, then the following procedure will require some adjustment. This adjustment requires that the accounting in Table 9.C-6 be maintained by size fraction because some material may be totally removed and not available for any removal during the next time interval. This could affect the expected scour or deposition depth.

TABLE 9.C-5 ⎯ **Sediment Characteristics**

Size Code*	Size Range (mm)	Geometric Mean Size D_i (mm)/(ft)	Material Gradation (%)
A	0.002 – 0.0625	0.011/0.000036	0.8
B	0.0625 – 0.125	0.088/0.00029	0.4
C	0.125 – 0.250	0.177/0.00059	14.2
D	0.250 – 0.50	0.354/0.0012	74.9
E	0.50 – 1.00	0.707/0.0023	5.0
F	1.00 – 2.00	1.41/0.0046	0.5
G	2.00 – 4.00	2.83/0.0093	0.2
			100.0

*See Table 9.C-6

TABLE 9.C-6 — Culvert Sediment Routing

1	2a	2b	3	4	5	6	7	8	9	10	11	12	13	14
	Inflow	Outflow	Trial	Trial	Trial Properties		Q_s	Sediment Class Delivered by Q_1						
Time	Q_1	Q_o	n	d_s	A	R	Total	A	B	C	D	E	F	G
(min)	(ft³/s)	(ft³/s)	(-)	(ft)	(ft²)	(-)	(ft³/s)	(ft³/s)	(ft³/s)	(ft³/s)	(ft³/s)	(ft³/s)	(ft³/s)	(ft³/s)
								Pre-flood sediment deposit in barrel						
0-5	19	18	0.030	3.90	16	1.20	0.0038	0	.0002	.0005	.0028	.0002	0	0
5-10	74	58	0.030	3.62	30	1.60	0.0267	.0002	.0012	.0038	.0200	.0013	.0001	0
10-15	205	100	0.030	3.20	38	1.80	0.0500	.0004	.0022	.0071	.0375	.0025	.0003	.0001
15-20	430	145	0.030	3.41	37	1.78	3.3260	.0266	.1463	.4723	2.491	.1663	.0166	.0067
20-25	385	185	0.030	3.48	37	1.78	2.5800	.0206	.1135	.3663	1.932	.1290	.0129	.0052
25-30	170	203	0.030	3.04	40	1.80	0.0470	.0004	.0021	.0067	.0352	.0024	.0002	.0001
30-35	110	198	0.030	2.57	40	1.85	0.0459	.0004	.0020	.0065	.0344	.0023	.0002	.0001
35-40	75	175	0.030	1.99	48	1.90	0.0274	.0002	.0012	.0039	.0205	.0014	.0001	.0001
40-45	50	140	0.030	1.36	49	1.95	0.0095	.0001	.0004	.0013	.0071	.0005	0	0
45-50	30	100	0.030	0.91	40	1.80	0.0040	0	.0002	.0006	.0030	.0002	0	0
50-55	15	70	0.030	0.53	36	1.70	0.0023	0	.0001	.0003	.0017	.0001	0	0
55-60	5	50	0.030	0.28	30	1.50	0.0003	0	0	0	.0002	0	0	0
60-70	0	25	0.030	0,02	20	1.25	0	0	0	0	0	0	0	0
70-80	0	5	0.012*	0	4	1.05	0	0	0	0	0	0	0	0

15	16	17	18	19	20	21	22	23	24
Q_{smax}	Sediment Class Transported by Q_o							Total	ΔQ_s	d_s
A	B	C	D	E	F	G	Total	ΔQ_s	Depth
(ft³/s)	(ft³/s)	(ft³/s)	(ft³/s)	(ft³/s)	(ft³/s)	(ft³/s)	(ft³/s)	(ft³/s)	(ft)
Pre-flood Sediment Deposit in Barrel									
0.4251	.0506	.0245	.0119	.0061	.0030	.0015	0.5227	-0.5189	3.90
1.234	.1469	.0712	.0345	.0178	.0088	.0043	1.518	-1.491	3.62
1.870	.2226	.1079	.0523	.0269	.0133	.0065	2.300	-2.249	3.20
1.790	.2131	.1033	.0501	.0258	.0127	.0062	2.201	1.125	3.41
1.790	.2131	.1033	.0501	.0258	.0127	.0062	2.201	0.3789	3.48
1.968	.2343	.1136	.0550	.0283	.0140	.0068	2.420	-2.373	3.04
2.052	.2443	.1184	.0574	.0300	.0146	.0071	2.523	-2.477	2.57
2.564	.3053	.1479	.0717	.0369	.0182	.0089	3.153	-3.326	1.98
2.723	.3242	.1571	.0762	.0392	.0191	.0094	3.348	-3.339	1.36
1.968	.2141	.1136	.0550	.0283	.0140	.0068	2.420	-2.416	0.91
1.624	.1934	.0937	.0454	.0234	.0115	.0056	2.000	-1.995	0.53
1.120	.1332	.0646	.0313	.0161	.0079	.0039	1.376	-1.376	0.28
0.5064	.0673	.0326	.0158	.0081	.0040	.0020	0.6952	-0.6952	0.02
0.0867	.0103	.0050	.0024	.0012	.0006	.0003	0.1067	-0.1067	-0.00*

*d_s = 0 since computed value is negative. Material in culvert has scoured out at this point in time.

The maximum culvert sediment transport rate, Q_{SMAX}, is estimated with Equation 9.C.4. This assessment ignores two perhaps offsetting but important facts:

- Upstream deposition of sediment due to temporary ponding would reduce the sediment amounts and characteristics delivered to the culvert entrance from that shown in Table 9.C-3 and Figure 9.C-3.

- Sediment would probably not be deposited uniformly throughout the culvert barrel but would be concentrated where minimum velocities occurred.

Assumptions used in this Example assessment are:

- Transported and deposited sediment characteristics are very similar.
- No armoring of deposited sediment occurs.
- A particular size fraction of deposited sediment is always readily available to be scoured.
- 4 ft of sediment is deposited throughout the length of this 200-ft culvert.

Where transported and deposited sediment characteristics are different, an accounting by size fraction is necessary because some size fractions may be totally removed and not available for further scour.

With an existing culvert, it may be possible to determine how deposition depths vary throughout the culvert length. If so, by expanding Table 9.C-6 to maintain a scour/deposition depth for incremental reaches within the culvert will allow an accounting to be maintained for each reach — similar to the accounting for the entire culvert as illustrated in Table 9.C-6. For a proposed culvert, a study of similar existing culverts may reveal some common deposition pattern for culverts.

To account for armoring is currently outside the scope of this *Manual*. Related to armoring is particle sorting, which determines the availability of a particular size fraction for scouring.

To assess the total change in the average 4 ft of sediment deposited throughout the length of this culvert at the beginning of the runoff event, it is necessary to route sediment through the culvert for all hydrograph time increments and sediment size fractions. Again, had the sediment characteristics in the barrel been significantly different from those transported to the culvert, then the computations would have been complicated. It would then be necessary to maintain an accounting by size fraction (termed Class in Table 9.C-6) to know if a particular size fraction had been totally removed and no longer had any material of that size available for transport during the next time increment.

This assessment practice is essentially an accounting process. The results are shown in Table 9.C-6. The following Steps illustrate how the data in each Column was obtained. The computations are for the first row in Table 9.C-6:

Column 1 — These are the time increments corresponding to the hydrograph of Figure 9.C-2. The difference between successive time increments, Δt, applies to that particular row in the table. For the first row, this would be $5 - 0 = 5$ minutes.

Column 2 — These are the average inflow and outflow discharges as taken from Figure 9.C-2. For the first row, this would be:

- Inflow = (0 + 38)/2 = 19 ft³/s
- Outflow = (0 + 36)/2 = 18 ft³/s

Column 3 —— If sediment deposits are expected to be present in the barrel, a higher trial Manning's n is selected than if the barrel is expected to be clean. Because Column 24 of the previous row shows 4 ft of sediment in the barrel and assuming that this sediment will not scour out during this time increment, try n = 0.030. This allows for increased roughness and possible bed forms.

Column 4 —— The trial depth, d_S, for deposited sediment may be larger or smaller than the value in Column 24 of the previous row depending on whether scour or deposition is expected. Assume that scour will occur and try a depth of 3.9 ft.

Column 5 —— From Figure 9.C-5a (or interpolating from Table 9.C-4), select the expected equivalent culvert waterway area, A, for the trial n and d_S. For a trial n = 0.030 and d_S = 3.9 ft of deposited sediment, this would be approximately 16 ft².

Column 6 —— Similar to Column 5, select an equivalent hydraulic radius, R, from Figure 9.C-5b (or interpolate from Table 9.C-4) and d_S = 3.9 ft, R is approximately 1.20 ft.

Column 7 —— The total volume of sediment delivered to the culvert is estimated from the sediment rating curve of Figure 9.C-3 (or Table 9.C-3). For an average inflow discharge of 19 ft³/s, the total sediment delivered to the Culvert, Q_s, is 0.0038 ft³/s.

Columns 8 through 15 —— Table 9.C-5 shows the characteristics of the sediment being delivered to the culvert. As noted earlier, this data is a "marriage" of bed sampling and the sediment transport technology contained in Reference *(1)*, Section 9.C.6. This material analysis also defines the size fractions (termed Class in this Example simply to minimize the width of the Table). Multiplying the percentage in each size fraction determines the volume of each fraction delivered to the site. In row one for Class D, this would be (0.74) (0.0038) = 0.0028 ft³/s of sediment. *Note: The total of Columns 8 through 14 should, considering rounding to four significant places, approximately equal Column 7.*

Columns 16 through 21 —— Using the trial equivalent Area, A, trial equivalent hydraulic radius, R, trial Manning's n, friction slope, S_f, and mean particle diameter for a particular size fraction (Class) from Table 9.C-5, compute the volume of sediment of this size fraction the culvert can be expected to transport using Equation 9.C.4. For Column 15, this would be as follows:

$$Q_{SMAX} = 3.78(32.2)^{0.5}(0.000036)^{-1.02}(0.001)^{2.52}(1.2)^{1.52}(16)$$
$$Q_{SMAX} = 0.4251 \text{ ft}^3/\text{s}$$

Note that, if the sediment characteristics of the material expected to be deposited in the culvert (or found to be present within an existing culvert) differ markedly from the characteristics of the sediment delivered to the culvert, then the amount of sediment that can be transported out of the culvert (or a reach of the culvert) may decrease once a particular size fraction has been removed from the culvert.

Column 22 —— This is the total of Columns 15 through 21. Due to rounding, this total may not be precisely the sum of these columns.

Column 23 — This is the difference between sediment delivered to the culvert (Column 7) and sediment transported through the culvert (Column 22). A negative value indicates that material is being scoured out of the culvert. A positive value indicates deposition. In row one, scour is occurring as 0.0038 – 0.5227 = – 0.5189 ft^3/s.

Column 24 — The total volume of scour or deposition is converted to an average depth of sediment in the culvert. In row one, the depth of sediment prior to this time increment from Column 24 of the previous row was 4 ft. The change in depth would be:

d_S = $(\Delta Q_s \Delta t$ 60 min/s)/(LB)
d_S = ((–0.5189 ft^3/s)(5 min)(60 min/s))/((200 ft)(8.0 ft))
d_S = −0.10 ft

This value is negative, indicating scour. The previous sediment depth was 4 ft. A new sediment depth d_S would then be 4.0 − 0.1 = 3.9 ft. Because this value agrees with the trial sediment depth for this time increment of 3.9 in Column 4, proceed to the next row.

Note: If this had not been a concrete box type structure, the culvert width, B, would have varied depending upon the expected sediment depth, d_S. A separate column in Table 9.C-6 might be required.

Conclusions — Table 9.C-6 suggests that the culvert will be scoured clean by the 100-yr event, but probably only well after the peak of 560 ft^3/s occurs. When the peak occurs, there will still be approximately 3.5 ft of sediment deposited in the culvert. Repeating the culvert flood routing (see Section 9.9) for an effective culvert size of approximately an 8-ft × 4.5-ft concrete box results in a disturbing finding — property will be damaged which was expected to be safe from a 100-yr flood hazard. Consideration should be given to installing a double 8-ft × 8-ft concrete box to accommodate for the loss of capacity due to expected sediment deposition. If this were an existing culvert, flood easements or retrofitting would be considerations.

This Example is a continuation of the high-velocity culvert from Appendix 9.A.6, Example. An assessment will be made as to whether the expected sediment deposition problems will be acceptable.

From the channel and morphology analysis, assume the following was determined:

- The downstream channel change slope, S_2, was constructed on the regime slope for the dominant discharge (see Reference *(1)*, Section 9.C.6) or S_2 = 0.0026 ft/ft.

- The culvert is a 9-ft × 9-ft concrete box.

- The unstable upstream channel slope, S_1, which is resulting in the sediment problem at this site is 0.036 ft/ft.

- The mean annual discharge is 250 ft^3/s, and the dominant discharge is 350 ft^3/s.

As a quick regime slope assessment, the average of the upstream and downstream slope is (0.0026 + 0.036)/2 or 0.0193 ft/ft. Sediment could deposit in the barrel on this slope as suggested by Figure 9.C-6, if the upstream sediment problem is not corrected. This amount of deposition would not meet the Design Criteria of Appendix 9.A.4 because more than half of the

inlet would be blocked. Further, any unexpected downstream aggradation would undoubtedly result in a sediment-blocked culvert. In Example 1 of Section 9.10, it was determined that the design discharge generated velocities sufficient to avoid sediment deposition. However, the concern now is that frequent low flows will not be sufficient to preclude deposition that would result in a blocked culvert when the design discharge occurs. A more rigorous analysis is considered justified.
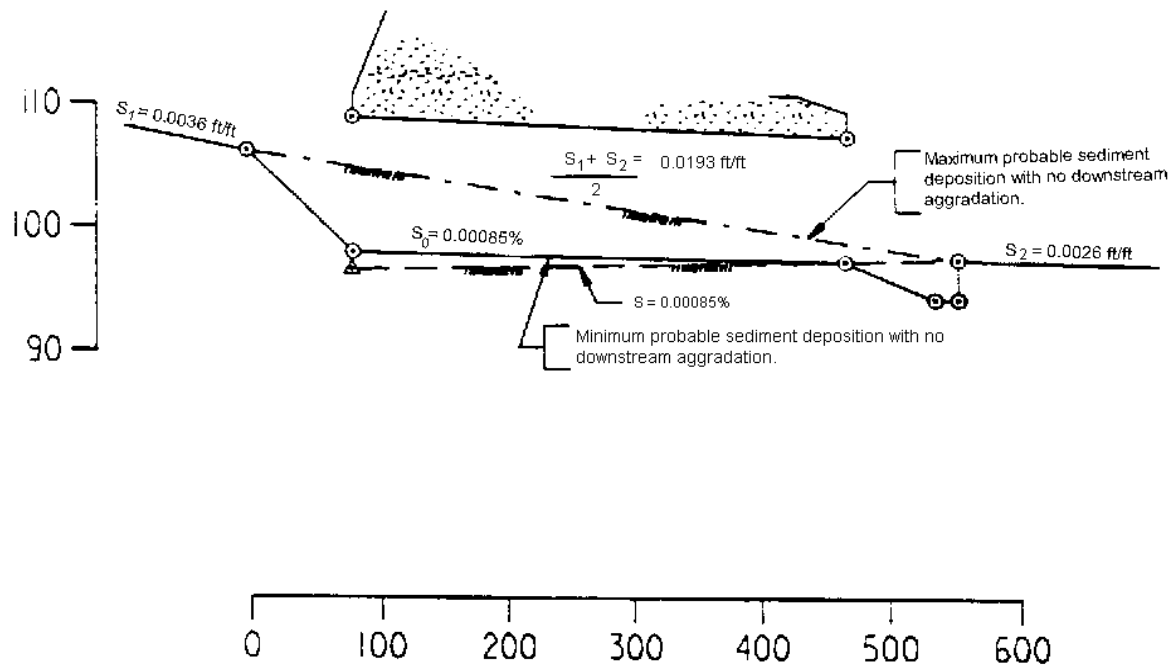
FIGURE 9.C-6 — Sediment Deposition

Consider the possibility that the mean annual (250 ft^3/s), or the dominant (350 ft^3/s), flow might be sufficient to keep this amount of sediment from collecting in the barrel:

MEAN ANNUAL. Using the tractive shear approach, compute the tractive shear for the mean annual flow (250 ft^3/s) in the barrel assuming that the sediment has deposited on a slope of S = 0.0193 ft/ft. Assume an appropriate Manning's n value for the deposited sediment to be 0.030 (allows for a margin of error should bed forms occur). Use common hydraulic tables (see Reference *(2)*, Section 9.C.6) to compute a flow depth with a culvert barrel width of B = 9 ft.

$$(Qn)/(B^{8/3}S^{1/2}) = ((250)(0.030))/((9.0^{8/3})(0.0193^{1/2})) = 0.154$$

From the tables:

$$D = 0.31 B$$
$$D = (0.31)(9.0) = 2.8 \text{ ft}$$

The actual tractive shear would be = τDS = (64.4)(2.8)(0.0193) = 3.48 lbs/ft^2, use 3.5 lbs/ft^2.

The critical tractive shear, τ_c, for the existing streambed material, which is assumed as the same for the deposited sediment, was selected during the morphology analysis to conservatively be approximately 0.5 lb/ft^2. Since 3.5 lbs/ft^2 is much greater than 0.5 lb/ft^2, even mean annual flows

will very likely scour this material out of the barrel. This also means that flows greater than the mean annual discharge will scour sediments deposited on a slope of 0.0193 ft/ft.

Assume that we have demonstrated that the mean annual flows will remove deposited sediment. What maximum slope could sediment be expected to reach? Assume only mean annual discharges occur over several years. Compute the slope for the critical tractive shear, τ_c, of 0.5 lbs/ft^2. A trial-and-error solution is necessary because depth D is a function of the slope, S. Again, using hydraulic tables:

Try S_o = 0.00085 ft/ft:

$(Qn)/(B^{8/3}S^{1/2})$ = $((250)(0.030))/((9.0^{8/3})(0.00085^{1/2}))$ = 0.73

D = 1.02B
D = (1.02)(9) = say 9.2 ft

$S = \tau_c/(\gamma D)$
S = 0.5/((64.4)(9.2))
S = 0.00084 ≈ 0.00085 ft/ft: OK

The culvert slope of 0.0044 ft/ft is greater than the critical tractive shear slope, S, of 0.00085 ft/ft. Thus, sediment deposited on a slope greater than 0.00085 ft/ft would be removed by the mean annual flow. It is concluded that sediment deposition will be somewhere between these two limits — probably closer to the lower limit. As such, a significant sediment deposition problem is unlikely to occur, unless there is an unexpected amount of downstream aggradation.

9.C.6 REFERENCES

(1) Federal Highway Administration, *River Engineering for Highway Encroachments — Highways in the River Environment,* Hydraulic Design Series No. 6, FHWA-NHI-01-004, December 2001.

(2) King, H.W. and Brater, E.F., *Handbook of Hydraulics,* Sixth Edition, McGraw-Hill Book Co., 1976.